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Effects of Corrugated Temperature Sheets on Optical Propagation

Andreas Muschinski
NORTHWEST RESEARCH ASSOCIATES INC.

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the atmospheric surface layer confirmed that angle-of-arrival fluctuations and irradiance fluctuations observed with large-aperture telescopes (36
cm aperture diameter) are consistent with theoretical predictions based on Taylor's frozen-turbulence hypothesis and the geometrical-optics
approximation. Short-term (less than a few seconds) fluctuations are dominated by turbulence while longer-term fluctuations are dominated by
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Abstract

Optical propagation through the clear atmosphere is affected by small-scale refractive-index fluctuations which are caused mainly by temperature fluctuations. In the stably stratified atmosphere, these temperature fluctuations are the result of a combination of (1) more or less homogeneous and isotropic turbulence and (2) non-turbulent, quasi-horizontal interfaces, or ``sheets". Collocated in-situ and optical field measurements conducted in the atmospheric surface layer confirmed that angle-of-arrival fluctuations and irradiance fluctuations observed with large-aperture telescopes (36 cm aperture diameter) are consistent with theoretical predictions based on Taylor's frozen-turbulence hypothesis and the geometrical-optics approximation. Short-term (less than a few seconds) fluctuations are dominated by turbulence while longer-term fluctuations are dominated by horizontally extended sheets. Direct numerical simulations of isotropic turbulence showed very good agreement with the turbulence spectrum predicted by Hill's 1978 model. A theoretical model of corrugated sheets was developed and analyzed.

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Effects of corrugated temperature sheets on optical propagation along quasi-horizontal paths in the stably stratified atmosphere

Final Report, Contract #FA9550-12-C-0070

AFOSR, *Remote Sensing and Imaging Physics* program

by Andreas Muschinski

(December, 2015)

Project Summary

Optical propagation through the clear atmosphere is affected by small-scale refractive-index fluctuations which are caused mainly by temperature fluctuations. In the stably stratified atmosphere, these temperature fluctuations are the result of a combination of (1) more or less homogeneous and isotropic turbulence and (2) non-turbulent, quasi-horizontal interfaces, or "sheets". Collocated in-situ and optical field measurements conducted in the atmospheric surface layer confirmed that angle-of-arrival fluctuations and irradiance fluctuations observed with large-aperture telescopes (36 cm aperture diameter) are consistent with theoretical predictions based on Taylor's frozen-turbulence hypothesis and the geometrical-optics approximation. Short-term (less than a few seconds) fluctuations are dominated by turbulence while longer-term fluctuations are dominated by horizontally extended sheets. Direct numerical simulations of isotropic turbulence showed very good agreement with the turbulence spectrum predicted by Hill's 1978 model. A theoretical model of corrugated sheets was developed and analyzed.

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1 Background

The modern physics of optical propagation through the turbulent atmosphere, pioneered by Tatarskii and coworkers in the 1950s and 1960s (Tatarskii, 1961, 1971), continues to be the conceptual basis for progress in various science and engineering disciplines, such as remote sensing of the optically clear atmosphere, astronomy, free-space optical communication, directed-energy technology, and terrestrial and extraterrestrial imaging and surveillance (e.g., Ishimaru, 1978; Strohbehn, 1978; Rytov et al., 1989; Roggemann and Welsh, 1996; Wheelon, 2001, 2003; Andrews and Phillips, 2005; Schmidt, 2010; Sasiela, 2007; Korotkova, 2014).

During the last decade or so, effects of anisotropic turbulence on optical propagation have become an important research focus within the optical-propagation community. So-called "non-Kolmogorov turbulence" models (e.g., Toselli et al., 2008; Toselli and Korotkova, 2015) have been introduced that deviate from the classical $-11/3$ power law predicted by the Obukhov-Corrsin theory of scalar turbulence. One goal of this project has been to develop, as an alternative to the "non-Kolmogorov turbulence" models, a statistical model of non-turbulent, non-overturning, corrugated interfaces, or "sheets" that have long been known to be ubiquitous in the stably stratified atmosphere (e.g., Doviak and Zrnić, 1984; Muschinski, 2004; Dalaudier et al., 1994; Muschinski and Wode, 1998).

2 Project Outcomes

In the following, we summarize the main project outcomes.

2.1 Observations

2.1.1 Optical measurements of cross-wind velocity

The temporal cross-correlation function of the angle-of-arrival (AOA) fluctuations of two optical waves propagating through atmospheric turbulence carries information regarding the average wind velocity transverse to the propagation path. In Tichkule and Muschinski (2012), we presented and discussed two estimators for the retrieval of the path-averaged, beam-transverse, horizontal wind velocity, v_t. Both methods retrieve v_t from the temporal cross-correlation function of AOA fluctuations obtained from two closely spaced, light-emitting diodes (LEDs). The first method relies on the time delay of the peak (TDP) of the cross-correlation function, and the second method exploits its slope at zero lag (SZL). Over a 9 h period during which v_t varied between $-1.3\ \mathrm{m\,s^{-1}}$ and $2.0\ \mathrm{m\,s^{-1}}$, the maximum rms difference between optically retrieved and in-situ measured, 10-s estimates of v_t was found to be $0.18\ \mathrm{m\,s^{-1}}$ for the TDP estimator and $0.23\ \mathrm{m\,s^{-1}}$ for the SZL estimator.

2.1.2 Wind-induced telescope vibrations

Turbulence in the atmospheric refractive-index field causes optical angle-of-arrival (AOA) fluctuations that can be used for atmospheric remote sensing of various parameters, including wind velocities and the optical refractive-index turbulence structure parameter, C_n^2. If AOA measurements are contaminated by wind-induced telescope vibrations, the underlying retrieval algorithms may fail. In order to study the effects of wind-driven telescope vibrations on optical-turbulence measurements, we conducted a field experiment in which we exposed two small telescopes deliberately to the wind (Tichkule and Muschinski, 2014). We measured AOA fluctuations of visible light propagating along a horizontal, 174 m long path 1.7 m above flat terrain, and we used fast-response ultrasonic anemometers to measure the wind velocity at multiple locations along the path. We found (1) that the AOA turbulence spectra were contaminated by multiple resonance peaks, (2) that the resonance frequencies were independent of the wind speed, and (3) that the AOA variance associated with the dominating vibration mode was proportional to the fourth power of the wind speed.

2.2 Theory

2.2.1 Homogeneous and isotropic turbulence

The three-dimensional (3D) spectrum $\Phi(\boldsymbol{\kappa})$ of the turbulent air temperature fluctuations is a key quantity for the physics of optical propagation through the turbulent atmosphere. The standard model, which was derived in the 1950s by Tatarskii from the Obukhov-Corrsin theory of homogeneous and isotropic turbulence, is $\Phi(\kappa) = 0.033\, C_T^2 \kappa^{-11/3} h(\kappa l_0)$, where $\kappa = |\boldsymbol{\kappa}|$ is the wave number, C_T^2 is the temperature structure parameter, l_0 is the inner temperature scale, and $h(\kappa l_0)$ is a universal function that approaches 1 for wave numbers in the inertial range and drops to zero for $\kappa l_0 \gg 1$. Certain performance characteristics of optical systems, such as the scintillation index for small receiving apertures, depend sensitively on the functional form of $h(y)$ at $y \approx 1$. During the last 70 years, the optical-turbulence community has developed and applied various heuristic $h(y)$ models. There is a constraint that any valid $h(y)$ model has to fulfill: $\int_0^\infty h(y) y^{1/3} dy = (27/10)\Gamma(1/3) = 7.233$. This constraint is a dimensionless form of the spectral temperature variance dissipation equation, which follows directly from first-principle fluid mechanics. In Muschinski (2015), we showed that Tatarskii's cut-off (Tatarskii, 1961) and Gaussian (Tatarskii, 1971) models fulfill this constraint while three more recent models, including the widely used Andrews model (Andrews, 1992), do not. The dissipation constraint can be used to "re-calibrate" the coefficients in these models.

2.2.2 Statistical model of corrugated temperature sheets

It is a standard assumption in the theory of optical propagation through the turbulent atmosphere that the refractive-index fluctuations $n_1(\mathbf{x})$ are statistically isotropic. It is well known, however, that $n_1(\mathbf{x})$ in the free atmosphere and in the nocturnal boundary layer is often strongly anisotropic, even at the smallest scales. We introduced and analyzed (Muschinski, 2016) a model atmosphere characterized by corrugated but non-overturning refractive-index interfaces, or "sheets," such that $n_1(\mathbf{x}) = v[z - h(x, y)]$, where $v(z)$ is a random function with a 1D spectrum $V(\kappa_z)$ that describes the vertical microstructure, and $h(x, y)$ is a random function of the horizontal coordinates x and y, which characterizes the local vertical displacement of the vertical microstructure. On the basis of some natural simplifying assumptions, we derived a closed-form expression for the 3D spectrum $\Phi(\boldsymbol{\kappa})$. This 3D spectrum differs from commonly used spectra in that the 3D spectral density decreases horizontally in the form of a Gaussian function, not as a power law. We show that if the vertical 1D spectrum follows a power law, then the horizontal 1D spectra follow the same power law but at a lower spectral level.

2.3 Computer simulations

For almost four decades, Hill's "Model 4" (Hill, 1978) has played a central role in research and technology of optical turbulence. Based on Batchelor's generalized Obukhov-Corrsin theory of scalar turbulence, Hill's model predicts the dimensionless function $h(\kappa l_0, \mathrm{Pr})$ that appears in Tatarskii's well-known equation for the three-dimensional refractive-index spectrum in the case of homogeneous and isotropic turbulence, $\Phi_n(\kappa) = 0.033\, C_n^2 \kappa^{-11/3} h(\kappa l_0, \mathrm{Pr})$. In Muschinski and de Bruyn Kops (2015), we investigated Hill's model by comparing numerical solutions of Hill's differential equation with scalar spectra estimated from direct numerical simulation (DNS) output data. Our DNS solved the Navier-Stokes equation for the three-dimensional velocity field and the scalar transport equation for the scalar field on a numerical grid containing 4096^3 grid points. Two independent DNS runs were analyzed, one with the Prandtl number $\mathrm{Pr} = 0.7$ and a second run with $\mathrm{Pr} = 1.0$. We found very good agreement between $h(\kappa l_0, \mathrm{Pr})$ estimated from the DNS output data and $h(\kappa l_0, \mathrm{Pr})$ predicted by the Hill model. We found that the height of the Hill bump is $1.79\,\mathrm{Pr}^{1/3}$, implying that there is no bump if $\mathrm{Pr} < 0.17$. Both the DNS and the Hill model predict that the viscous-diffusive "tail" of $h(\kappa l_0, \mathrm{Pr})$ is exponential, not Gaussian.

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